ARMY RESEARCH LABORATORY

Ballistic Impact Behavior of Novel Coextruded Polycarbonate/ Polymethyl Methacrylate Multilayers

by Alex J. Hsieh, Daniel C. DeSchepper, and John W. Song

ARL-TR-1821

October 1998

Abstract

Ballistic impact behavior of coextruded polycarbonate (PC)/polymethyl methacrylate (PMMA) composites consisting of 256, 1024, 2048, and 4096 layers with various composition has been evaluated. The individual layer thickness of PMMA was determined to be critical for the impact response of these multilayers. A brittle/ductile transition occurred as evidenced by a significant increase in the damage zone size when the PMMA layer thickness was reduced to approximately 0.3 to 0.4 μm; a mixed mode of failure resulted in these composites. Such improvement in ballistic performance can be achieved through either an increase in the total number of layers or a reduction in the PMMA content. With the PMMA layer thickness further reduced to approximately 0.15 μm, ductile deformation, which was predominant in the PC control, occurred in the PC/PMMA multilayers, and the resulted damage zone was limited to the immediate vicinity of impact. A brittle mode of failure, however, was encountered in all the PC/PMMA composites as the thickness of PMMA layers reached 0.5 μm or higher, regardless of their composition and layer configuration. Results of the ballistic impact energy measurements also revealed that the PMMA layer thickness was the critical parameter, and the determined impact energy values were consistently higher for the multilayers with PMMA layer thickness being 0.15 μm or thinner. In addition, microcracking in PMMA appeared to be the dominant mode of failure. Stress concentration associated with these microcracks in PMMA appeared to be insignificant to promote crack propagation across the ductile PC layers when the layer thickness of PMMA is below its critical value.

Acknowledgments

Dr. Alex Hsieh would like to acknowledge the FY97 U.S. Army Research Laboratory (ARL) Director's Research Initiative funding, which allowed for the initiation of this exploratory research. The authors would like to thank Ms. Julia Kerns of Case Western Reserve University for the preparation of coextruded PC/PMMA multilayers and Mr. Alex Gutierrez at the Polymers Research Branch, Weapons and Materials Research Directorate, ARL, for his computer expertise. In addition, Mr. Gume Rodriguez at the Polymers Research Branch, Weapons and Materials Research Directorate, ARL, is thanked for his careful review of this manuscript.

INTENTIONALLY LEFT BLANK

Table of Contents

INTENTIONALLY LEFT BLANK

List of Figures

INTENTIONALLY LEFT BLANK

List of Tables

INTENTIONALLY LEFT BLANK

1. Introduction

The Army has a continuous interest in emerging polymeric materials for current transparent lightweight armor and future Army After Next materiel systems. Polycarbonate (PC) and polymethyl methacrylate (PMMA) are currently used in many applications including windshields, canopies, vision blocks, face shields, goggles, and lenses. PMMA has excellent optical clarity and high yield strength, but it is brittle upon impact. PC, on the other hand, has outstanding ballistic impact strength; however, it has poor chemical resistance and can scratch easily. Hard coatings are needed for most commercial PC's; however, a hard coating capable of providing resistance to chemical attack or abrasion hazard may in some cases cause an adverse effect on the impact performance of the coated PC. Our earlier studies on PC coated with diamond-like carbon (DLC) have elucidated that a good hard coating system should have an optimized coating thickness and optimized micromechanical properties.

The unique material characteristics of DLC coatings generally with thickness in either micrometers or submicrometers provide a motivation for the design and development of polymeric multilayers with individual layer thickness on the order of micrometer- or submicrometer-scale level. This has been accomplished by using an innovative coextrusion multiplying technique available at Case Western Reserve University for the development of model multilayered composites by incorporating PMMA into PC to achieve better durability. The technical challenges reside upon the compatibility between the ductile PC and brittle PMMA as well as upon the ability to enhance the overall barrier properties without the expense of impact strength of PC. Our first hypothesis is that the scale of flaws or damage and the stress intensity associated with these defects will be small when the layer thickness is significantly reduced. Secondly, propagation of cracks once initiated in the brittle PMMA phase will be suppressed when these cracks encounter the ductile PC layers.

This work examines the ballistic performance of coextruded PC/PMMA multilayered composites that consist of different numbers of layers and various component compositions. The role of individual layer thickness upon the overall ballistic strength will be determined. In

addition, an attempt of this study is to provide a better understanding of failure mechanisms encountered in these multilayers during the impact; therefore, better design of coextruded composites with alternate ductile and brittle layers can be accomplished.

2. Experimental

PC/PMMA multilayers were fabricated using an unique coextrusion multiplying process available at Case Western Reserve University. During the microlayer coextrusion, PC and PMMA melts were fed from two separate single screw extruders through a coextrusion block as parallel layers, followed by a series of die elements. Each die element doubles the number of layers as shown in Figure 1 [1]; it first splits the viscoelastic melts vertically (stage B), then compresses and spreads each half horizontally (stage C), and finally recombines them (stage D). Therefore, a coextruded multilayer consisting of alternating PC and PMMA with $2^{(n+1)}$ layers can be fabricated using a set of n die elements. The feed ratios and total number of layers were varied in order to produce coextruded composites with desired individual layer thicknesses. In this study, two sets of PC/PMMA composites were prepared. The first group included multilayers with the number of layers being 256, 1024, and 2048 and with the amount of PMMA varying from 20 to 80 volume-percent. The second set of PC/PMMA multilayers was designed with higher PC content such as 80, 90, and 95 volume-percent and with the number of layers being 2048 and 4096.

Ballistic impact measurements were carried out using a helium gas gun apparatus. A mutilayered PC/PMMA test specimen of approximately 4 in by 4 in was mounted between two aluminum plates with a 2-in-diameter opening, and the plates were firmly tightened. The sample holder was then placed and clamped in the center of the ballistic impact test apparatus, and the PC/PMMA multilayer was subjected to the impact of a fragment-simulating projectile of 1.1-g (17 grain) weight and 0.22-in diameter. Four light screens were used as triggers for timers to record the time-of-flight of the projectile to determine the velocity of the projectile before and after impact [2]. The range of impact velocity was between 120 and 160 m/s. The ballistic impact energy, which is a measure of kinetic energy absorbed or dissipated by the samples upon

impact, can be calculated following equation (1) with an assumption that the mass (M) of the projectile is constant during its penetration into the target.

$$\text{Ballistic Impact Energy} = 1/2\ M\ (V_s^2 - V_r^2), \tag{1}$$

where V_s and V_r are the striking and residual velocities, respectively.

Photographs of ballistic impact test specimens were taken using a Kodak DCS 420 digital camera. Post-processing of photographs was done using PhotoShop software to ensure resolution.

3. Results and Discussion

3.1 Ballistic Impact Behavior

Figure 2 shows the photographs of the PC control and 256-layer PC/PMMA multilayers after ballistic impact. All the multilayers with 35, 50, 65, and 80 volume-percent of PC displayed brittle failure as compared to a ductile deformation observed in the PC control. A circular pattern was clearly seen in the pure PC; however, it was not observed in any of the 256-layer composites. This ring characteristic was a result of impact of the sample holder frame, which had a circular opening upon the test specimen, indicating the extent of stress wave propagation during the impact.

A significant reduction in the ballistic impact strength of a 256-layer PC/PMMA multilayer with only 20 volume-percent of PMMA revealed that the presence of a brittle PMMA phase strongly affects the ductility of PC. Therefore, multilayers with thinner layer thickness were fabricated through an increase in the total number of layers (i.e., 1024 and 2048 layers) to examine the compatibility of a ductile PC with a brittle PMMA. These coextruded PC/PMMA multilayers consisted of PMMA with 20, 35, 50, 65, and 85 volume-percent. Figure 3 displays the photographs of 1024-layer PC/PMMA multilayers after ballistic impact; the ballistic

performance was apparently better in the composite with 80 volume-percent of PC, where deformation involving a larger area resulted. A brittle mode of failure, however, occurred in all the other 1024-layer multilayers with less than 80 volume-percent of PC.

In the 2048-layer multilayers as shown in Figure 4, a significantly improved ballistic impact resistance was clearly seen in the composite with 80 volume-percent of PC. In the latter, a ring pattern was apparent, indicating that the extent of stress wave propagation was significant and similar to that as observed in the PC control. The characteristic of ductile deformation, which only occurred in the 80-volume-percent PC, 2048-layer composite, further indicated that the layer thickness of PMMA is critical in determining the impact performance of these coextruded PC/PMMA multilayers. This effect was demonstrated in Figure 5 for the comparison of ballistic response of 256-, 1024-, and 2048-layer composites with the amount of PC in all three being 80 volume-percent.

Table 1 lists the average thickness of coextruded PC/PMMA multilayers, in which the calculated individual layer thickness of PC and PMMA is also included. The overall sheet thickness of the 256- and 1024-layer composites (about 1 to 1.3 mm) was slightly thinner than that of the 2048-layer multilayers (about 1.3 to 1.5 mm). The critical layer thickness of PMMA appeared to be about 0.3 μm for these PC/PMMA multilayers to favor ductile deformation upon ballistic impact. The role of PMMA layer thickness was further investigated using composites with either a further increase in the total number of layers such as 4096-layer or an increase of the PC content up to 90 and 95 volume-percent. Figures 6a, 6b, and 6c show the ballistic impact results of the 4096-layer PC/PMMA composites; it is obvious that a ductile deformation occurred in all of these multilayers in which the amount of PC was 80, 90, and 95 volume-percent, respectively, and the corresponding layer thicknesses of PMMA were approximately 0.17 μm or thinner. The ring pattern shown in each of these multilayers clearly demonstrated the extent of stress wave propagation that indeed occurred across the whole test specimen during the impact. Ductile failure and a ring pattern were also evident in Figures 7a and 7b for the 2048-layer PC/PMMA composites with 90 and 95 volume-percent of PC, respectively. The layer thickness

of the corresponding composite with 90 volume-percent of PC is approximately 0.14 μm, which is about the same as that of the 80-volume-percent PC, 4096-layer multilayer.

Figure 8 compares the ballistic impact behavior of the PC control with those of 1024-, 2048-, and 4096-layer multilayers in which the PC contents were 80% or higher. A mixed mode of failure occurred in both the 1024- and 2048-layer composites with 80 volume-percent of PC (as those seen in Figure 5), indicating the reproducibility of the fracture behavior. In addition, these impact results confirmed the layer thickness of PMMA in the proximity of 0.3 or 0.4 μm to be critical for the presence of a brittle/ductile transition to occur in the PC/PMMA multilayers. The mixed-mode failure mechanism was further examined, and the results are shown in Figure 9 for all the 2048-layer composites with 80 volume-percent of PC. It is obvious the damage zone area that resulted in the brittle/ductile transition was significantly larger than that associated in either a brittle or ductile failure. Table 2 lists the calculated layer thickness of PC/PMMA multilayers in which the PMMA layer thickness was reduced.

It is apparent that the individual layer thickness of PMMA plays a critical role in determining the ballistic impact behavior of these PC/PMMA multilayers. In addition, microcracking in PMMA appeared to be dominant; stress concentration associated with these microcracks determined the ultimate mode of failure. It was insignificant to promote rapid crack propagation across the ductile PC layers once the PMMA layer thickness was reduced to approximately 0.14 μm. On the other hand, multilayers with PMMA layer thickness greater than 0.4 μm always failed in a brittle fashion regardless of the composite configuration.

3.2 Measurements of Ballistic Impact Energy

The kinetic energy absorbed or dissipated during the projectile penetration was determined only for those PC/PMMA composites that encountered complete penetration. Since the overall thickness was not consistent for all the multilayers, the calculated ballistic impact energy was normalized by the thickness of each laminate. Table 3 summarizes all the normalized ballistic impact energy values obtained for the available PC/PMMA multilayers.

Although the normalized ballistic impact energy data as shown in Figure 10 were scattered, a strong dependence of the ballistic impact strength upon the PC content was clearly seen. For multilayers with less than 65 volume-percent of PC (shown in the shaded region A), the determined values were relatively low, and little improvement in the ballistic performance was seen as the PC content increased. The low ballistic impact energy values corresponded to a brittle mode of failure observed in the corresponding 256-, 1024-, and 2048-layer PC/PMMA multilayers. A drastic increase in the ballistic impact energy occurred when the amount of PC was above 80 volume-percent, particularly 90 and 95 volume-percent (as shown in the shaded region B). Ductile deformation occurred in the multilayers in which their composition fell in the region B; however, a brittle/ductile transition appeared to be present between 65 and 80 volume-percent of PC. The latter was dependent upon the total number of layers of the PC/PMMA composites.

Since the PMMA layer thickness was determined to be critical, we then replotted the normalized ballistic impact energy values as a function of PMMA layer thickness (as shown in Figure 11) for all the PC/PMMA multilayers with different composition and different number of layers. It is clear that the normalized ballistic impact energy values significantly increased as the PMMA layer thickness was reduced to about 0.15 μm or thinner. Ballistic impact performance was poor for PC/PMMA multilayers with the PMMA layer thickness approximately 0.5 μm or thicker, regardless of their composition and layer configuration.

4. Conclusion

This was the first exploratory investigation into the scale effect of brittle and ductile domains upon the ballistic impact behavior of coextruded PC/PMMA composites. This report has elucidated the failure mechanisms encountered in these multilayers upon impact. The individual layer thickness of PMMA appeared to be critical in the determination of ballistic impact response of these multilayers. Ballistic impact energy was significantly increased when the PMMA layer thickness was reduced to approximately 0.15 μm or thinner. This desired thickness can be achieved through either an increase in the total number of layers or an increase

in the PC content. As a result, ductile failure occurred in the corresponding PC/PMMA multilayers, which is similar to that observed in the PC control. The damage zone associated with the ductile deformation was limited to the immediate vicinity of impact, and a ring characteristic apparent on the fracture surface indicated the significant extent of the stress wave propagation. A brittle mode of failure, however, was encountered in all the PC/PMMA composites as the thickness of PMMA layers reached 0.5 μm or higher, regardless of their composition and layer configuration. Microcracking in the PMMA layers appeared to be the dominant mode of failure; delamination between the layers did not occur in any PC/PMMA multilayers that failed either in a ductile or brittle mode. Furthermore, stress concentration or intensity factor associated with these PMMA microcracks appeared to be insignificant to promote crack propagation across the ductile PC layers when the layer thickness of PMMA was controlled to below its critical value.

This work clearly outlined a design rationale for achieving coextruded composites with better ballistic performance. In addition, the impact results of PC/PMMA multilayers confirmed our earlier observation on DLC coating: a thinner layer thickness of the brittle PMMA component in the former and a thin but hard DLC in the latter both sustained the ductility of PC. Since the role of PMMA in these multilayers is to enhance barrier properties and scratch resistance of PC, proper control of PMMA layer thickness is rather important for the coextruded multilayers to achieve optimized ballistic impact strength and durability.

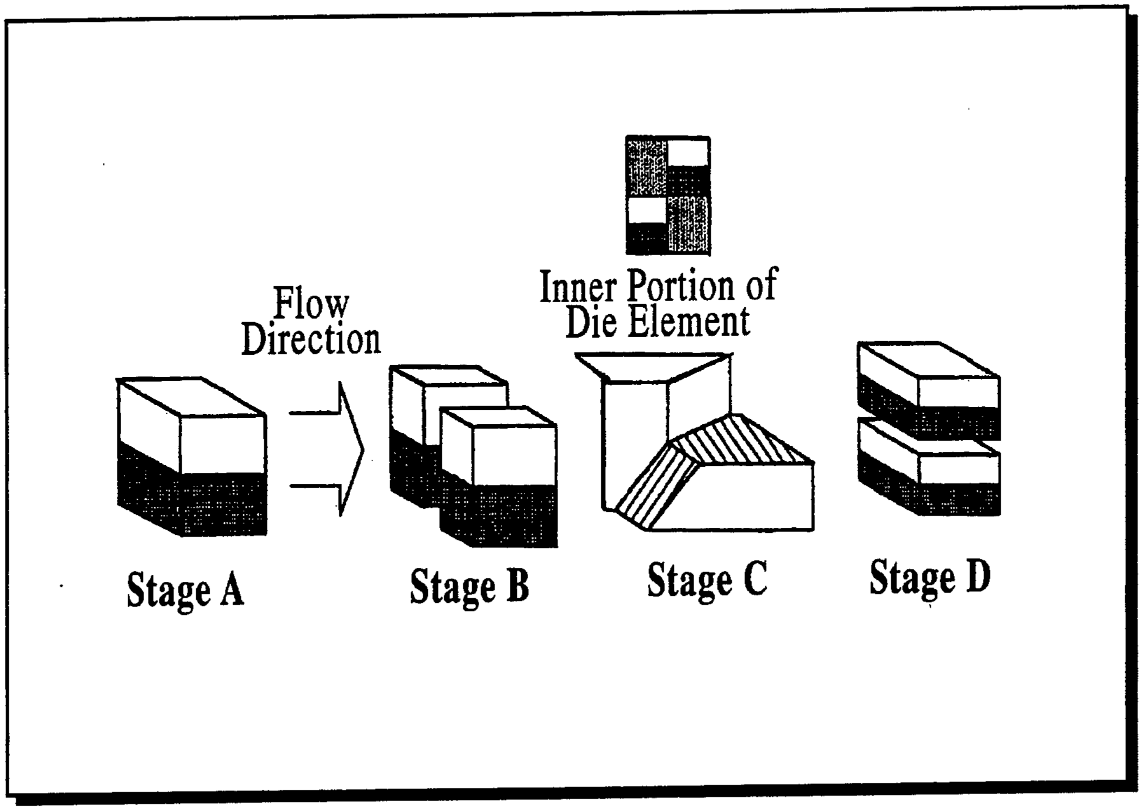

Figure 1. A Schematic Showing Cutting and Stacking of the Polymer Melts Flowing Through the First Multilayering Die Element.

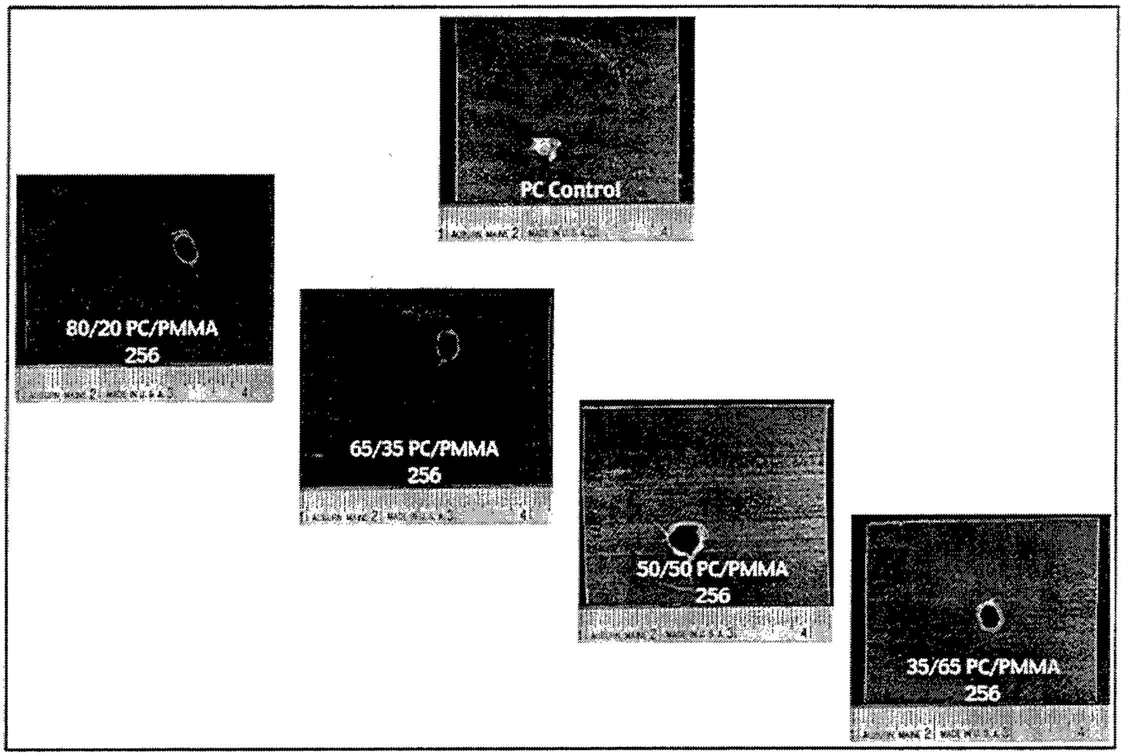

Figure 2. Photographs of Ballistic Response of 256-Layer PC/PMMA Multilayers.

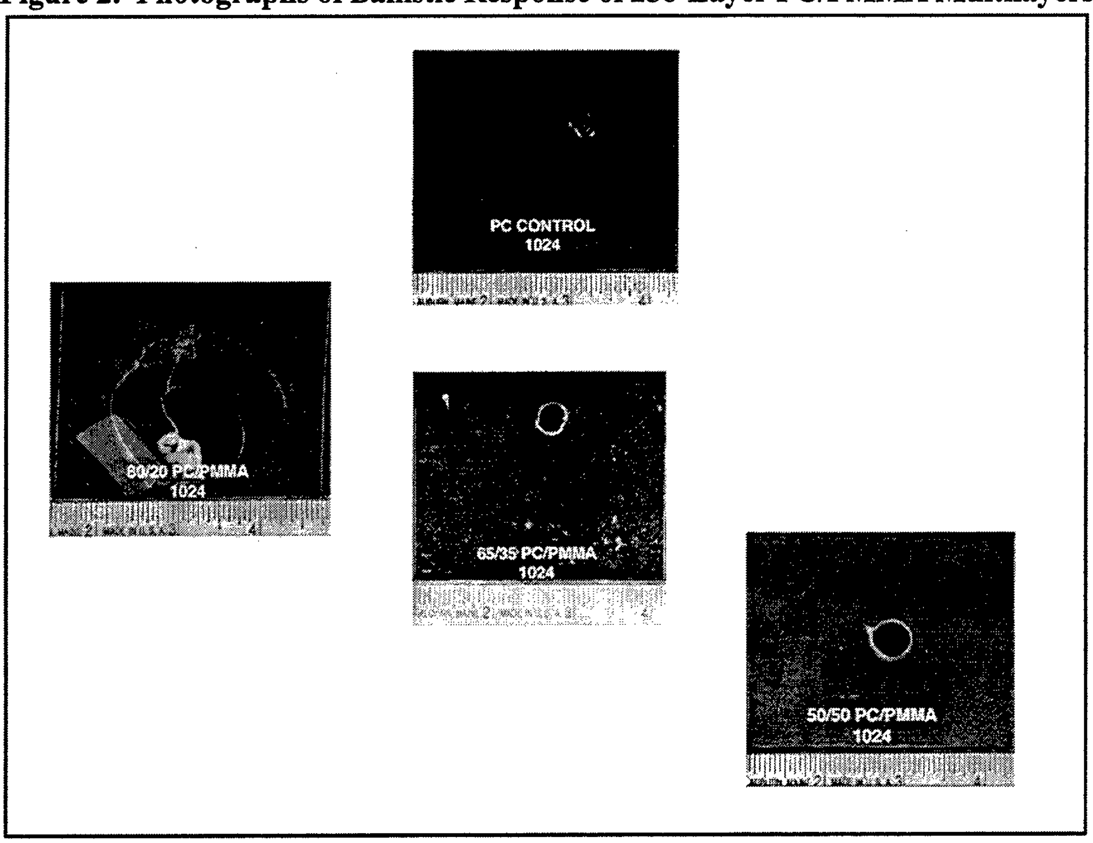

Figure 3. Photographs of Ballistic Response of 1024-Layer PC/PMMA Multilayers.

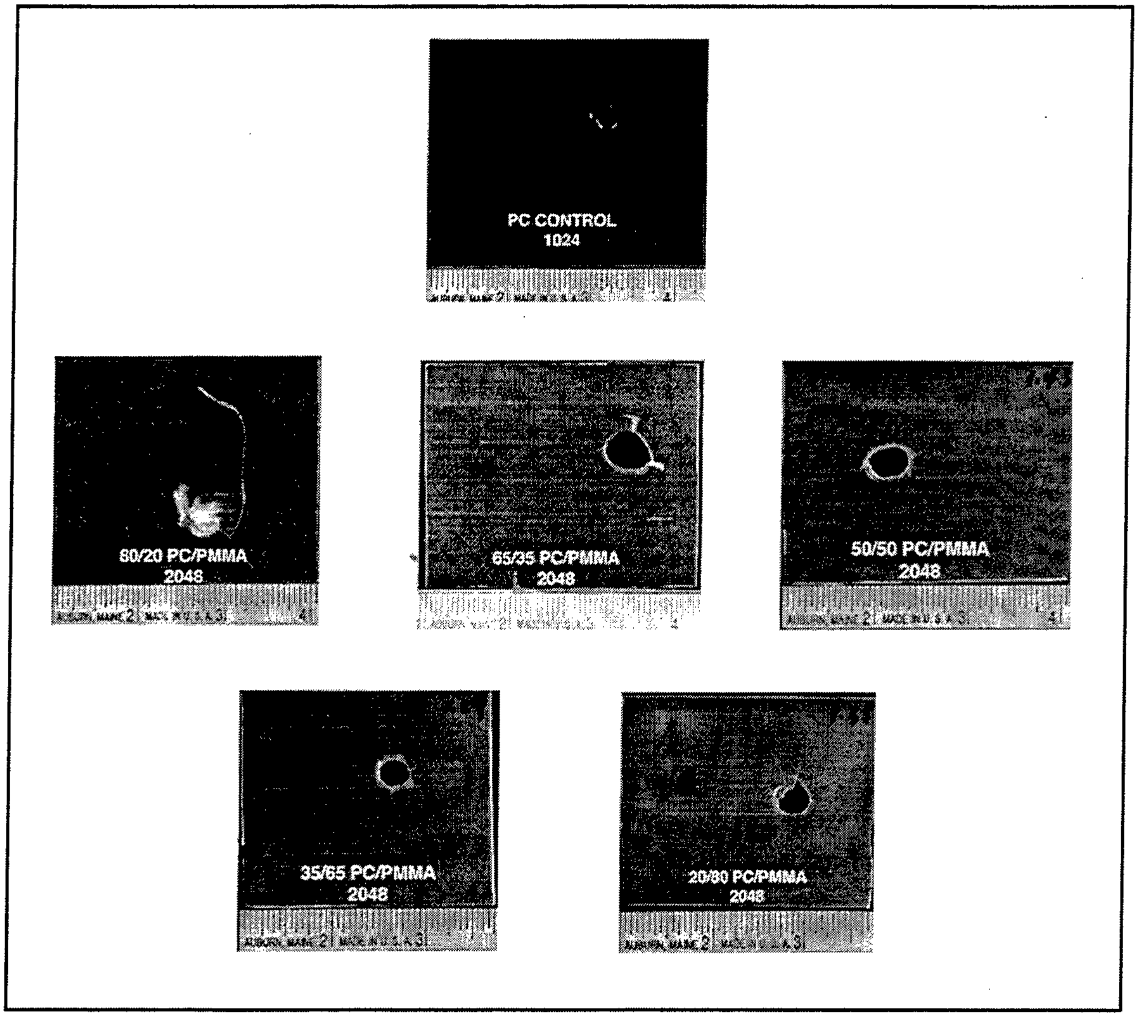

Figure 4. Photographs of Ballistic Response of 2048-Layer PC/PMMA Multilayers.

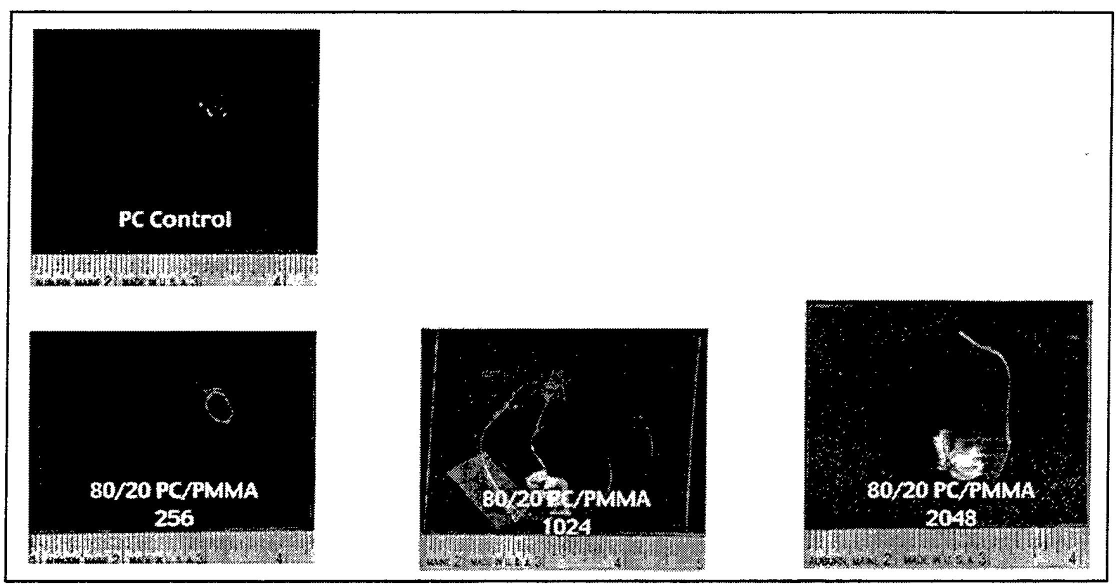

Figure 5. Comparison of Ballistic Response of 256-, 1024-, and 2048-Layer PC/PMMA Multilayers With 80 Volume-Percent of PC.

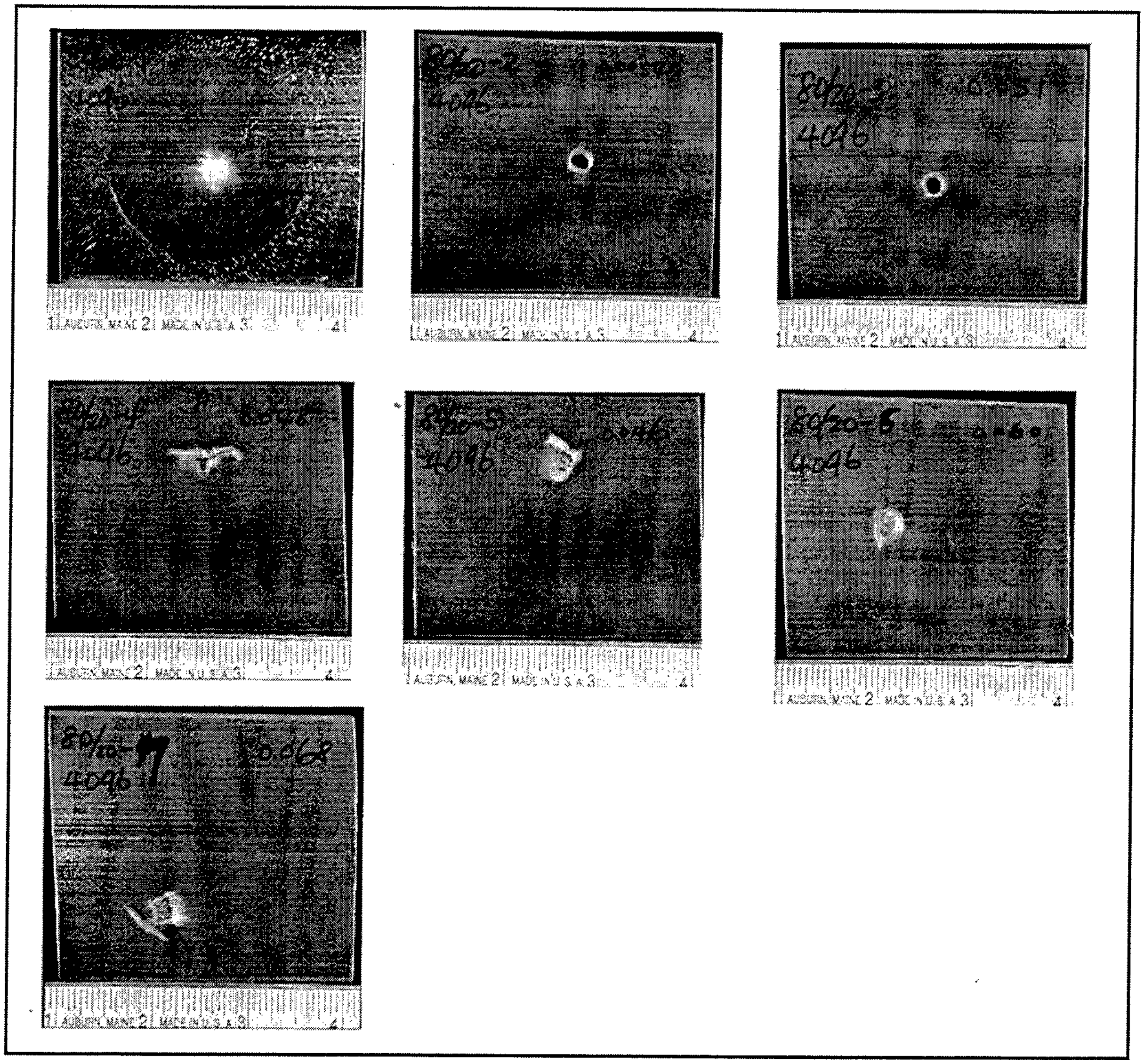

Figure 6a. Photographs of Ballistic Response of 4096-Layer PC/PMMA Multilayers With 80 Volume-Percent of PC.

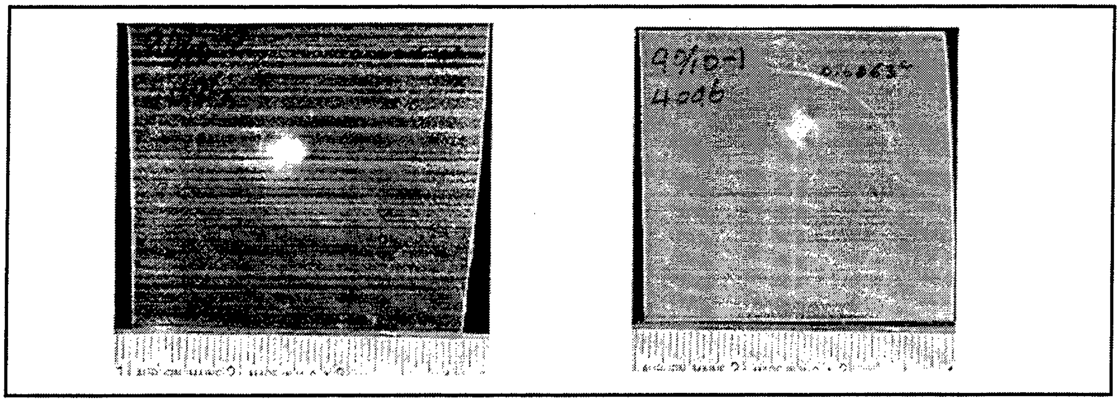

Figure 6b. Photographs of Ballistic Response of 4096-Layer PC/PMMA Multilayers With 90 Volume-Percent of PC.

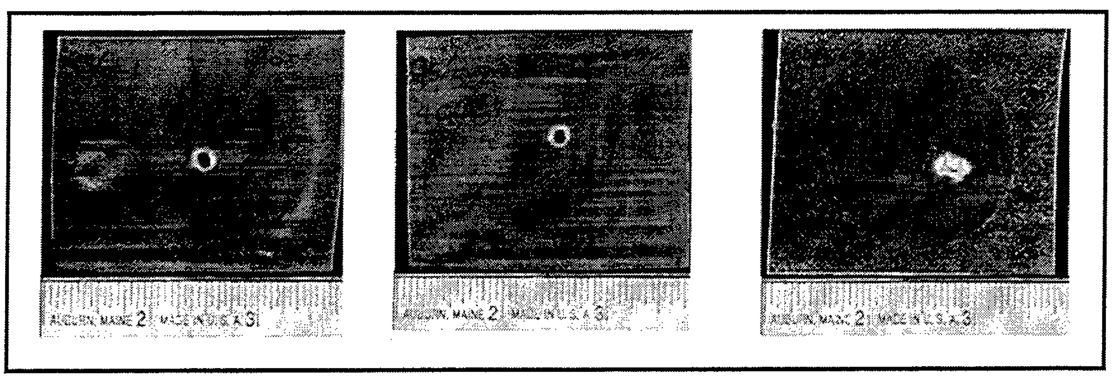

Figure 6c. Photographs of Ballistic Response of 4096-Layer PC/PMMA Multilayers With 95 Volume-Percent of PC.

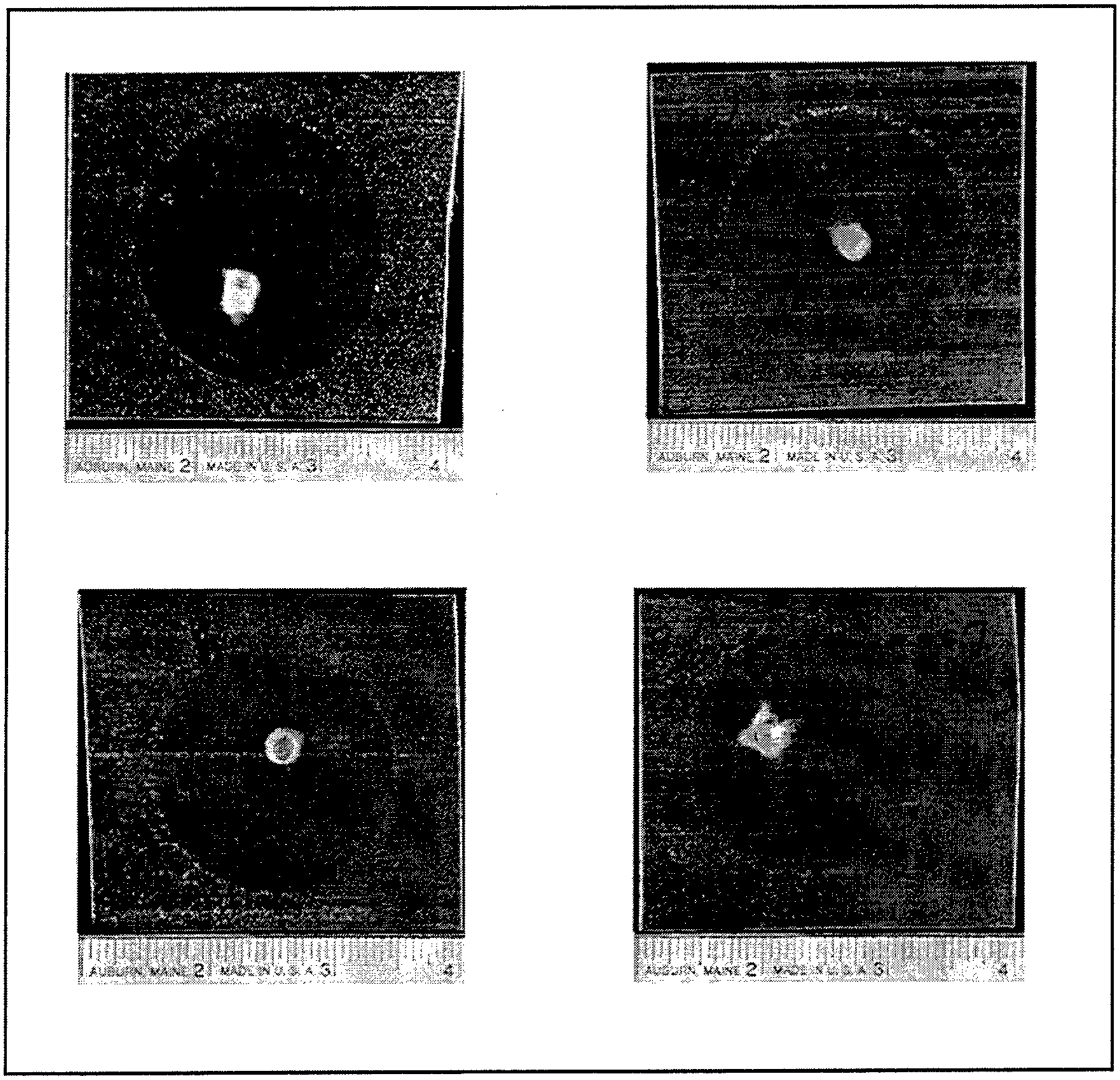

Figure 7a. Photographs of Ballistic Response of 2048-Layer PC/PMMA Multilayers With 90 Volume-Percent of PC.

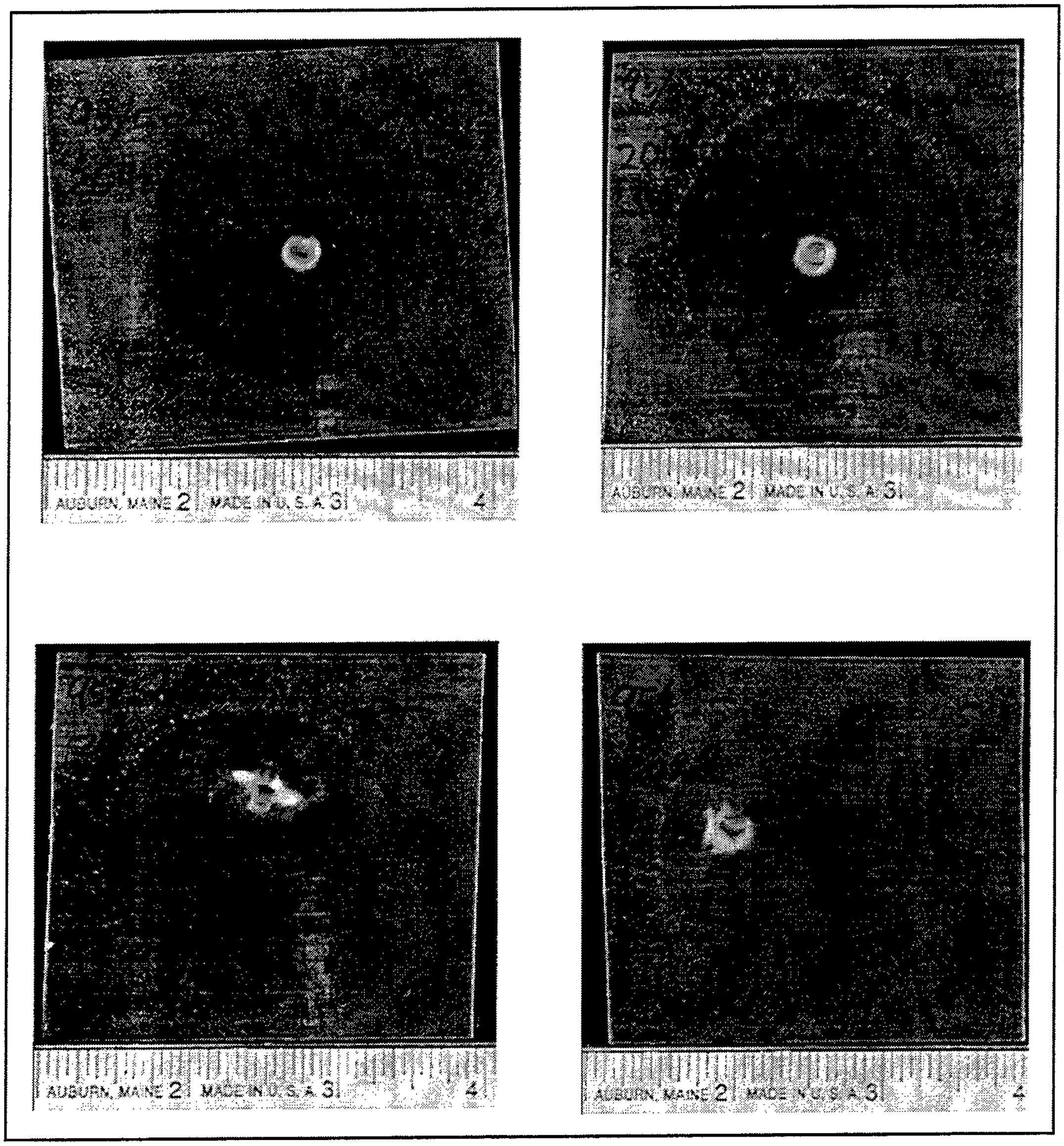

Figure 7b. Photographs of Ballistic Response of 2048-Layer PC/PMMA Multilayers With 95 Volume-Percent of PC.

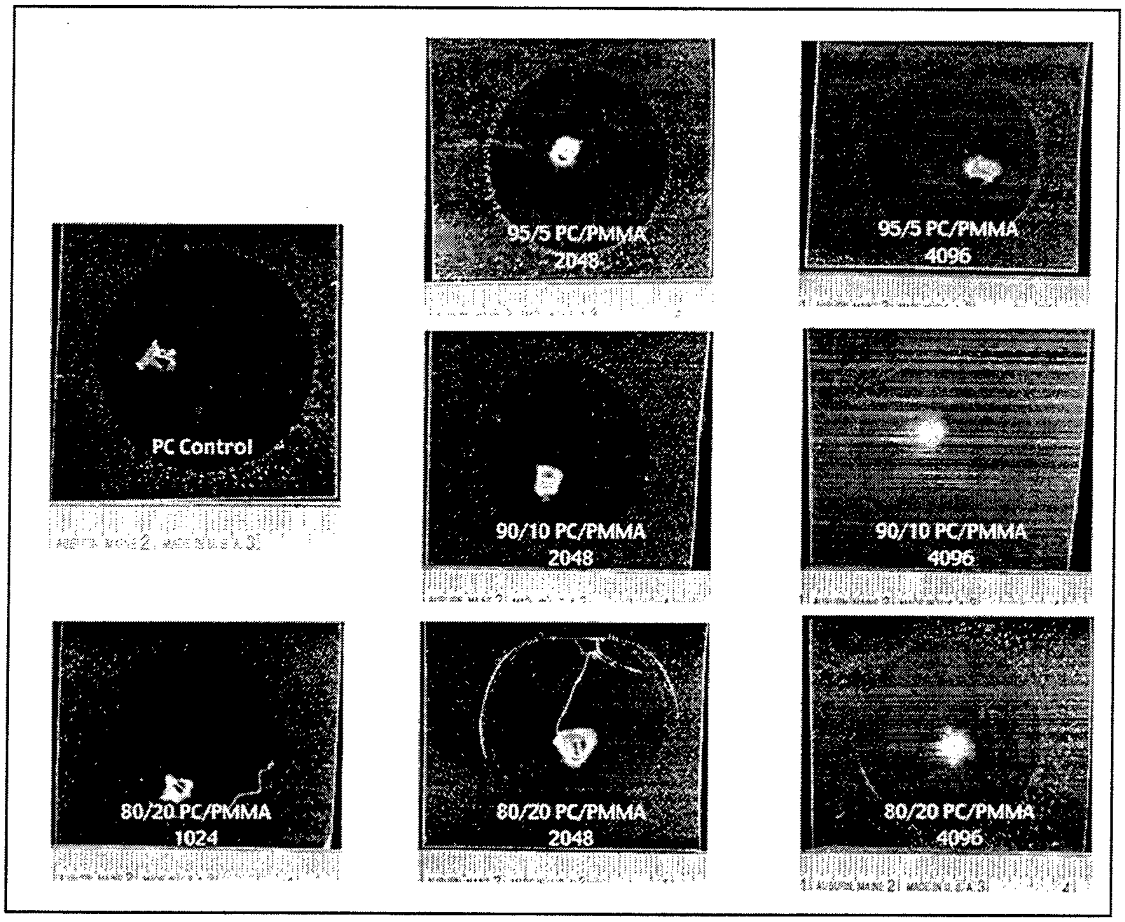

Figure 8. Photographs Comparing the Ballistic Response of 1024-, 2048-, and 4096-Layer PC/PMMA Multilayers With 80, 90, or 95 Volume-Percent of PC.

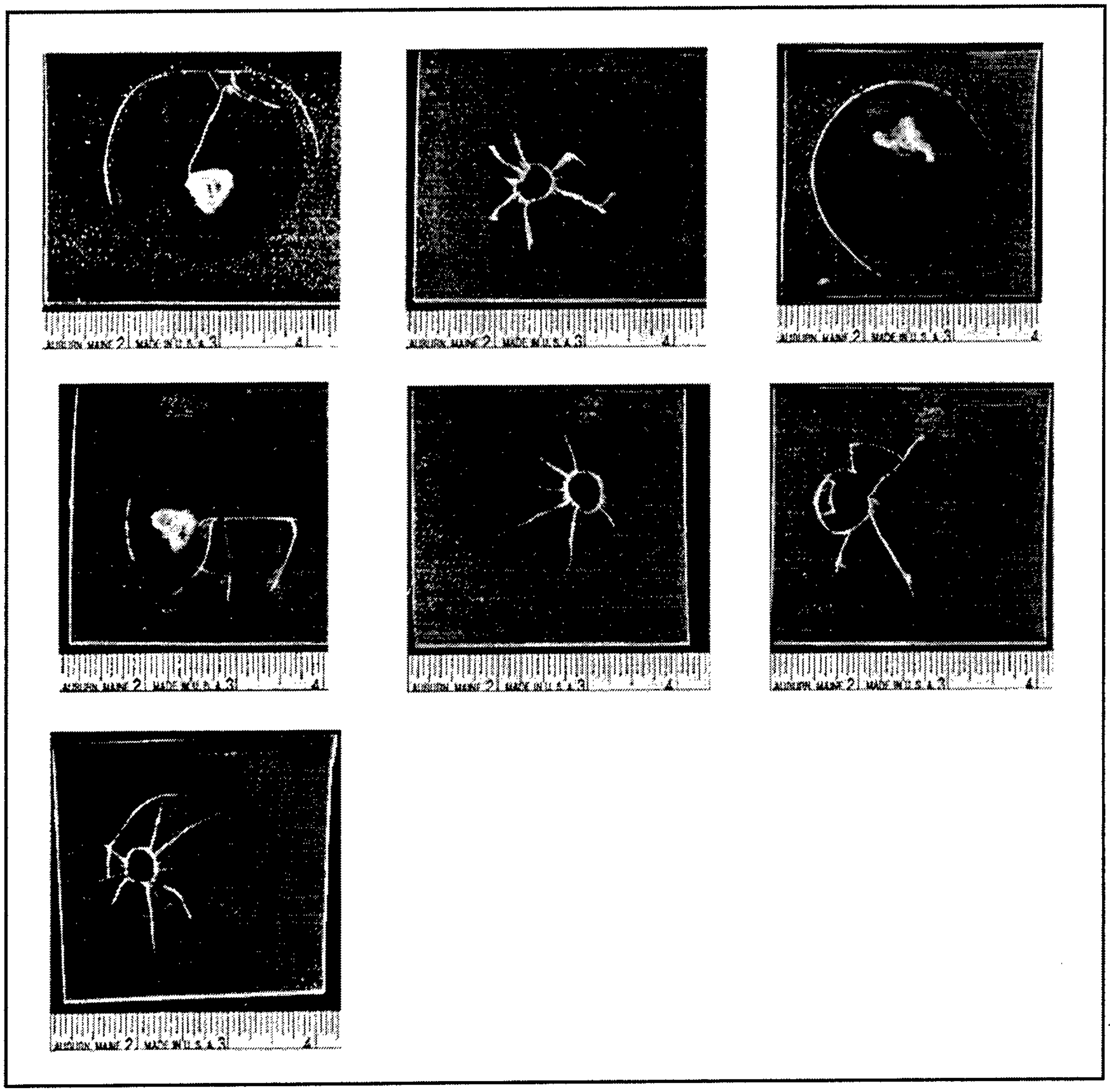

Figure 9. Photographs Showing a Mixed Mode of Failure Upon Ballistic Impact of 2048-Layer PC/PMMA Multilayers With 80 Volume-Percent of PC.

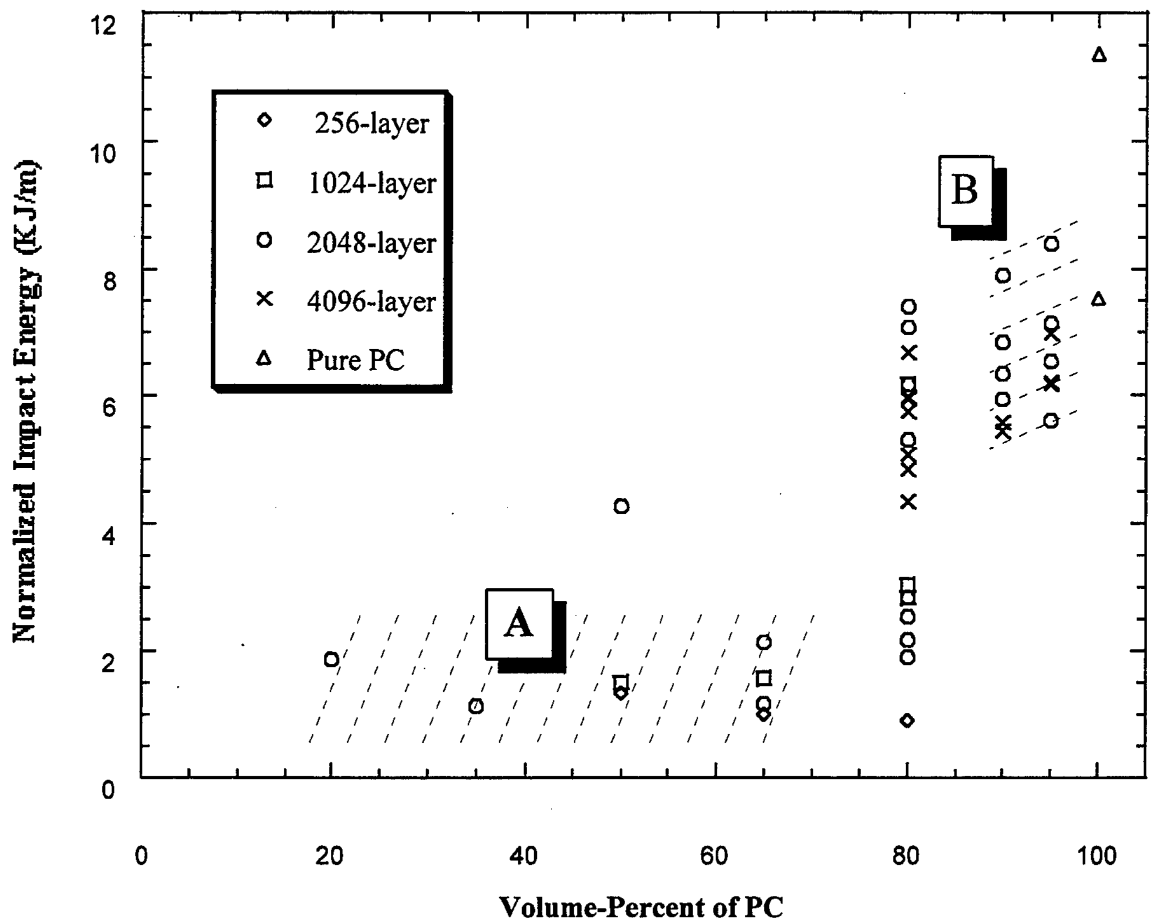

Figure 10. Plot of Normalized Ballistic Impact Energy Values as a Function of Volume-Percent of PC and Total Number of Layers; Shaded Region A and Region B Within Which Multilayers Failed in a Brittle and Ductile Mode, Respectively.

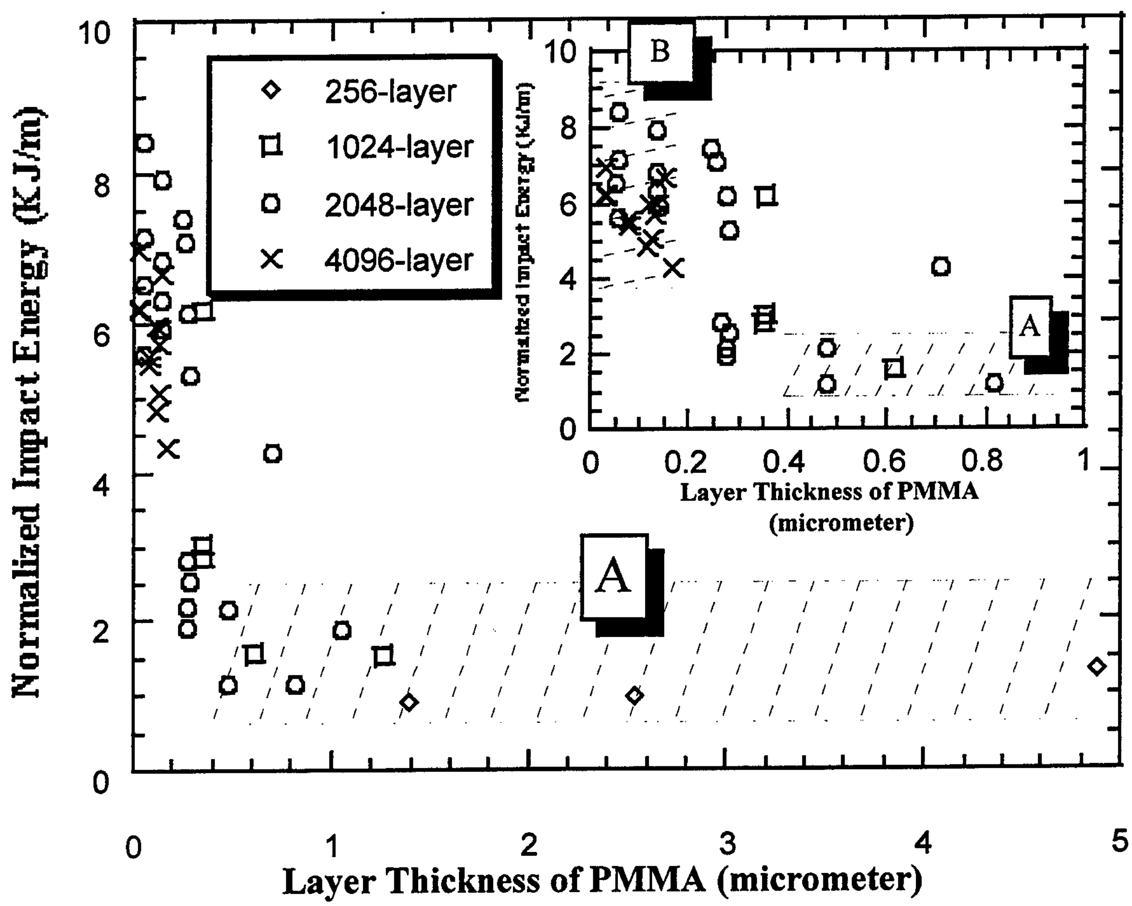

Figure 11. Plot of Normalized Ballistic Impact Energy Values vs. PMMA Layer Thickness; The Insert Is an Enlarged Plot of PMMA Layer Thickness Smaller Than 1 μm; Shaded Region A and Region B Within Which Multilayers Failed in a Brittle and Ductile Mode, Respectively.

Table 1. Average Sheet Thickness of 256-, 1024-, and 2048-Layer PC/PMMA Multilayers and the Calculated Individual Layer Thickness of PC and PMMA for the Corresponding Composites

PC/PMMA	256- layer		1024- layer		2048- layer	
	sheet thickness (mm)	layer thickness (μm)	sheet thickness (mm)	layer thickness (μm)	sheet thickness (mm)	layer thickness (μm)
80/20	0.89	5.6/1.4	0.9	1.4/0.4	1.31	1.0/0.3
65/35	0.93	4.7/2.5	0.9	1.1/0.6	1.4	0.9/0.5
50/50	1.25	4.9/4.9	1.29	1.3/1.3	1.45	0.7/0.7
35/65	n.a.	n.a.	n.a.	n.a.	1.29	0.4/0.8
20/80	n.a.	n.a.	n.a.	n.a.	1.35	0.3/1.1

Table 2. Average Sheet Thickness of 256-, 1024-, and 2048-Layer PC/PMMA Multilayers and the Calculated Individual Layer Thickness of PC and PMMA for the Corresponding Composites

PC/PMMA	1024- layer		2048- layer		4096- layer	
	sheet thickness (mm)	layer thickness (μm)	sheet thickness (mm)	layer thickness (μm)	sheet thickness (mm)	layer thickness (μm)
95/ 5	n.a.	n.a.	1.1	1.0/0.05	1.26	0.6/0.03
90/10	n.a.	n.a.	1.4	1.2/0.14	1.62	0.7/0.08
80/20	0.9	1.4/0.4	1.4	1.1/0.3	1.4	0.5/0.14

Table 3. Normalized Ballistic Impact Energy Data and Calculated Individual PMMA Layer Thickness of the Available 256-, 1024-, 2048-, and 4096-Layer PC/PMMA Multilayers

PC/PMMA Multilayers	Ind. PMMA Layer (mm)	Normalized Impact Energy (KJ/m)
256-layer		
80/20	1.39	0.9
65/35	2.54	0.99
50/50	4.88	1.34
1024-layer		
80/20	0.35	6.17
80/20	0.36	3.04
80/20	0.35	2.84
65/35	0.62	1.57
50/50	1.26	1.52
2048-layer		
95/5	0.05	6.54
95/5	0.06	7.14
95/5	0.06	5.61
95/5	0.06	8.39
90/10	0.14	6.33
90/10	0.14	6.84
90/10	0.14	7.91
90/10	0.14	5.94
80/20	0.26	7.08
80/20	0.28	1.92
80/20	0.28	2.18
80/20	0.28	2.54
80/20	0.28	6.16
80/20	0.28	5.3
80/20	0.27	2.83
80/20	0.24	7.4
65/35	0.48	1.16
65/35	0.48	2.15
50/50	0.71	4.28
35/65	0.82	1.15
20/80	1.05	1.87
4096-layer		
95/5	0.03	6.22
95/5	0.03	6.18
95/5	0.03	6.97
90/10	0.08	5.45
90/10	0.08	5.56
80/20	0.13	5.73
80/20	0.13	5.95
80/20	0.13	5.08
80/20	0.12	5.97
80/20	0.11	4.84
80/20	0.15	6.66
80/20	0.17	4.34

INTENTIONALLY LEFT BLANK

5. References

1. Mueller, C. D., S. Nazarenko, T. Ebeling, T. L. Schuman, A. Hiltner, and E. Baer. "Novel Structures by Microlayer Coextrusion - Talc-Filled PP, PC/SAN, and HDPE/LLDPE." *Polymer Engineering and Science*, vol. 37, no. 2, pp. 355–362, Feb. 1997.

2. Song, J. W., and R. Allen. "Effect of Resin Crosslinking in Aramid Composites on Ballistic Impact Resistance." Natick/TR-87/040L, U.S. Army Natick Research, Development, and Engineering Center, Natick, MA, 1987.

INTENTIONALLY LEFT BLANK

NO. OF COPIES	ORGANIZATION
2	DEFENSE TECHNICAL INFORMATION CENTER DTIC DDA 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218
1	HQDA DAMO FDQ D SCHMIDT 400 ARMY PENTAGON WASHINGTON DC 20310-0460
1	OSD OUSD(A&T)/ODDDR&E(R) R J TREW THE PENTAGON WASHINGTON DC 20301-7100
1	DPTY CG FOR RDE HQ US ARMY MATERIEL CMD AMCRD MG CALDWELL 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
1	INST FOR ADVNCD TCHNLGY THE UNIV OF TEXAS AT AUSTIN PO BOX 202797 AUSTIN TX 78720-2797
1	DARPA B KASPAR 3701 N FAIRFAX DR ARLINGTON VA 22203-1714
1	NAVAL SURFACE WARFARE CTR CODE B07 J PENNELLA 17320 DAHLGREN RD BLDG 1470 RM 1101 DAHLGREN VA 22448-5100
1	US MILITARY ACADEMY MATH SCI CTR OF EXCELLENCE DEPT OF MATHEMATICAL SCI MAJ M D PHILLIPS THAYER HALL WEST POINT NY 10996-1786

NO. OF COPIES	ORGANIZATION
1	DIRECTOR US ARMY RESEARCH LAB AMSRL D J W LYONS 2800 POWDER MILL RD ADELPHI MD 20783-1145
1	DIRECTOR US ARMY RESEARCH LAB AMSRL DD J J ROCCHIO 2800 POWDER MILL RD ADELPHI MD 20783-1145
1	DIRECTOR US ARMY RESEARCH LAB AMSRL CS AS (RECORDS MGMT) 2800 POWDER MILL RD ADELPHI MD 20783-1145
3	DIRECTOR US ARMY RESEARCH LAB AMSRL CI LL 2800 POWDER MILL RD ADELPHI MD 20783-1145
	ABERDEEN PROVING GROUND
4	DIR USARL AMSRL CI LP (305)

NO. OF COPIES	ORGANIZATION
	ABERDEEN PROVING GROUND
70	DIR USARL AMSRL WM MA A J HSIEH

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 1998	Final, Jan - Jun 98

4. TITLE AND SUBTITLE
Ballistic Impact Behavior of Novel Coextruded Polycarbonate/Polymethyl Methacrylate Multilayers

5. FUNDING NUMBERS
1L162618AH80

6. AUTHOR(S)
Alex J. Hsieh, Daniel C. DeSchepper, and John W. Song*

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRL-WM-MA
Aberdeen Proving Ground, MD 21005-5069

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-1821

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

10.SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
*U.S. Army Natick Research, Development, and Engineering Center

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Ballistic impact behavior of coextruded polycarbonate (PC)/polymethyl methacrylate (PMMA) composites consisting of 256, 1024, 2048, and 4096 layers with various composition has been evaluated. The individual layer thickness of PMMA was determined to be critical for the impact response of these multilayers. A brittle/ductile transition occurred as evidenced by a significant increase in the damage zone size when the PMMA layer thickness was reduced to approximately 0.3 to 0.4 μm; a mixed mode of failure resulted in these composites. With the PMMA layer thickness further reduced to approximately 0.15 μm, ductile deformation, which was predominant in the PC control, occurred in the PC/PMMA multilayers, and the resulted damage zone was limited to the immediate vicinity of impact. A brittle mode of failure, however, was encountered in all the PC/PMMA composites as the thickness of PMMA layers reached 0.5 μm or higher, regardless of their composition and layer configuration. Results of the ballistic impact energy measurements also revealed that the PMMA layer thickness was the critical parameter, and the determined impact energy values were consistently higher for the multilayers with PMMA layer thickness being 0.15 μm or thinner. In addition, microcracking in PMMA appeared to be the dominant mode of failure. Stress concentration associated with these microcracks in PMMA appeared to be insignificant to promote crack propagation across the ductile PC layers when the layer thickness of PMMA is below its critical value.

14. SUBJECT TERMS
ballistic impact, coextruded multilayers, failure mechanism, microcracking

15. NUMBER OF PAGES
31

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18 298-102

INTENTIONALLY LEFT BLANK.

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. ARL Report Number/Author ARL-TR-1821 Date of Report November 1998

2. Date Report Received ______

3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) ______

4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.) ______

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. ______

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) ______

CURRENT ADDRESS

Organization

Name E-mail Name

Street or P.O. Box No.

City, State, Zip Code

7. If indicating a Change of Address or Address Correction, please provide the Current or Correct address above and the Old or Incorrect address below.

OLD ADDRESS

Organization

Name

Street or P.O. Box No.

City, State, Zip Code

(Remove this sheet, fold as indicated, tape closed, and mail.)

(DO NOT STAPLE)